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BRADFORD OIL FIELD

(Preliminary Report)

by

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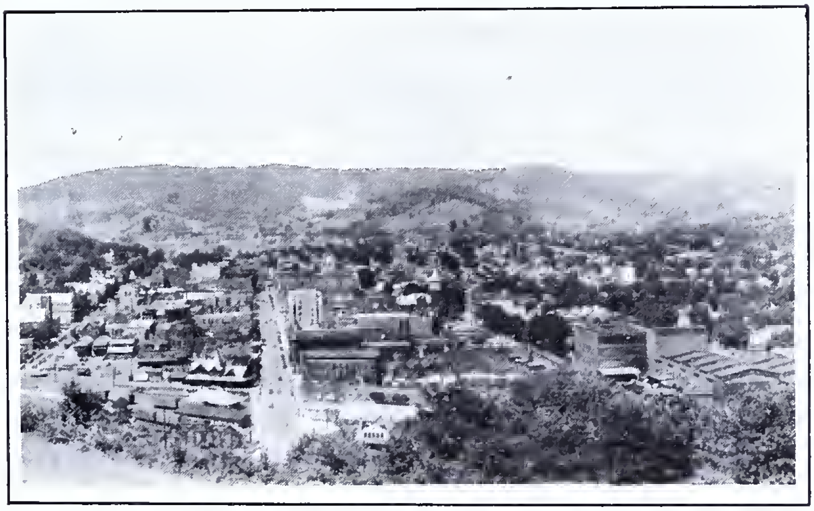

Bradford, Pennsylvania

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CONTENTS

Page

Introduction 1
- Location and size 1
- Topography 1

Stratigraphy 1
- Pennsylvanian system 1
  - Pottsville series 1
- Upper Devonian series 2
  - Knapp formation 2
  - Oswayo formation 2
  - Cattaraugus formation 2
  - Chemung group 3
  - Portage group 4
  - Genesee black shale 4
  - Tully limestone 4
- Middle Devonian series 4
  - Hamilton group 4
  - Onondaga limestone 4
- Lower Devonian series 4
  - Oriskany sandstone 4
  - Helderberg group 4
- Silurian and Ordovician systems 4

Geologic structure 4
- Regional 4
  - Folding 5
  - Dip 5
- Local structure 5
  - Surface structure 5
  - Subsurface structure 5

Bradford Third sand 6
- Lateral and vertical variations 6
- Conditions of sedimentation 7

Bradford pool 8
- Reserves and future life of pool 8
- Estimate of oil content 9

Methods and results of water-flooding 10
- Relation of production of oil by water-flooding to physical characteristics of sand 10
- Summary of production data 11

ILLUSTRATIONS

Figure 1. Outcrop and surface structure of Bradford district . . 14
2. Structure map of Bradford oil field 14
3. Structure map of Bradford district 15
4. Oil and gas map of Bradford district 16
5. Section and porosity and permeability profiles of Core 11. 17

GEOLOGY AND OIL RESOURCES OF THE BRADFORD FIELD,*

PENNSYLVANIA AND NEW YORK

By Chas. R. Fettke.

INTRODUCTION

The Bradford Oil Field of northwestern Pennsylvania and adjacent New York State produced 352,700,000 barrels of oil from 1871 to 1936, inclusive. Present methods of production probably will raise the total output to 500,000,000 barrels. The remarkable success attained recently in applying artificially-conducted water as a drive to increase the extraction of oil from a pool that had almost reached the economic limit by ordinary production methods, has attracted world-wide attention. Almost all the Bradford production has come from a single horizon, the Bradford Third sand, which has proven productive over a continuous area of 84,000 acres. This gives the Bradford pool major rank among the great oil pools of the United States, eighth (1) in 1934 in total production, but also places it second with respect to total continuous productive area. Its total is exceeded only by the recently discovered East Texas pool, with an area of 116,580 acres.(2)

Location and size. The Bradford Oil Field lies mainly in the north-central part of McKean County, Pennsylvania, the third from the west of the northern tier of counties. Approximately 14 percent of the field is in Cattaraugus County, New York. Smaller detached pools also productive in the Bradford Third sand include an additional 8,500 acres and lie around the eastern and southern margins of the main pool. Several small pools, in part overlapping those already mentioned, yield gas and some oil from sands occurring above and below the Bradford Third sand.

Topography. The Bradford district is one of comparatively rugged topography, with maximum differences in elevation of nearly 1,000 feet. In the northern part the divides and valleys are narrow and steep sided; in the southern part the divides form a gently undulating plateau incised by steep-walled narrow gorges. Most of the area is wooded. Only the broad valley floors, a small part of the immediately adjacent slopes along the lower portions of the major streams, and relatively small tracts on the upland area in the southern part, are cleared. The flats are underlain by unconsolidated alluvium, in some places reaching maximum depths of 250 feet, which was deposited during the Pleistocene glaciation. Since then the streams have cut shallow channels into the alluvial deposits of the flat floors. These alluvial deposits furnish much of the water now used for flooding purposes.

STRATIGRAPHY

In addition to the unconsolidated alluvial deposits of Quaternary age referred to, more than 1,000 feet of rock strata of lower Pennsylvanian to upper Devonian age are exposed in the district. Nearly 6,000 feet more have been explored with the drill, the deepest well reaching Upper Ordovician strata.

PENNSYLVANIAN SYSTEM.

Pottsville Series. The youngest bedrock belongs to the Pottsville series of the Pennsylvanian system and forms the broad plateau between the head-waters of Tunungwant and Kinzua Creeks which is underlain by about 170 feet of Pottsville strata. Pottsville rocks also cap most of the high hills in the northwestern part and the high ridge in the northern part of the field but are absent in the northeastern.

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* This is a preliminary and brief report only. The complete report will be printed as soon as funds are available.

(1) The Oil and Gas Journal, January 31, 1935. p.6.

(2) Reistle, C. E., Jr., East Texas production. Drilling and production practice in 1934. American Petroleum Institute, 1935, p.96.

The following members beginning at the top are represented in the district: Mercer shale and coal, Connoquenessing sandstone, Sharon shale and coal, and Olean conglomerate.

UPPER DEVONIAN SERIES

Knapp formation. Glenn applied the term Knapp to the formation immediately underlying the Olean conglomerate at the village of Knapp Creek in southern Cattaraugus County, New York.(3) Here it has a thickness of 65 feet and consists of two conglomeritic beds separated by a varying thickness of shale. S. H. Cathcart, of the Pennsylvania Geological Survey, has recently determined that the upper Knapp probably is equivalent to the lower Corry.

Over that portion of the Bradford district west of the East Branch of Tunungwant Creek, the lower of the two conglomerates is usually present. Not more than one conglomerate was observed at any locality, the balance of the Knapp interval being occupied by sandstone and shale. Most of the pebbles in the conglomerate are rounded; however, in contrast to the ovoid or ellipsoidal Olean conglomerate pebbles, they tend to be flat or discoidal. Red jasper pebbles, absent from the Olean, occur sparingly throughout the Knapp conglomerate.

East of the East Branch of Tunungwant Creek, the conglomerate is rarely seen, its place being taken by sandstone. It is, therefore, difficult to draw the line between the Knapp and the Oswayo in this area as the Knapp sandstones resemble some of the interbedded sandstones associated with the underlying Oswayo shales.

Due to the beveling of the gently southerly-dipping strata by the Mississippian-Pennsylvanian unconformity, the interval from the base of the lower Knapp conglomerate to the base of the Olean increases from 66 feet at the head of Hedgehog Hollow to 187 feet in the vicinity of Guffey. The sandy shales and associated shaly sandstone immediately underlying the Olean at Guffey are believed to occupy the stratigraphic position of the Hayfield shale of Erie and Crawford Counties.

Oswayo formation. The Oswayo formation, named from Oswayo Creek, New York, comprises the greenish-gray sandy shales with interbedded shaly and frequently fossiliferous sandstone layers beneath the Knapp and above the Cattaraugus red beds in the Bradford region.

This formation varies little in thickness in the Bradford district. At the head of Fourmile Creek, nine miles northeast of Bradford, the thickness is 209 feet; at the head of Hedgehog Hollow, three miles northwest of Bradford, 198 feet; and at Guffey, 14 miles south, 213 feet. About 60 feet above the base of the Oswayo, locally, there occurs a limestone from one to three feet thick which Ashburner called the Marvin Creek.(4) It consists largely of broken brachiopod and other marine shells imbedded in a sandy matrix.

Cattaraugus formation. The name Cattaraugus(5) was given by Glenn to the 300 to 350 feet of red shales interbedded with greenish-gray shales and fine-grained, greenish-gray, thin-bedded, micaceous sandstones which occur between the Oswayo and the Chemung shales in Cattaraugus County, New York, and extend southward into Pennsylvania. Glenn recognized three rather well-defined conglomerate horizons in the Cattaraugus formation in the Olean and Salamanca quadrangles, namely, the Tuna (Killbuck) at the top, the Salamanca near the middle, and the Wolf Creek at the base. All of these conglomerates have flat or discoidal quartz pebbles and occasional red jasper pebbles. In the Bradford district a fine-grained, greenish-gray, micaceous and argillaceous sandstone frequently occurs immediately over the highest red shale, but the Tuna conglomerate was not seen. The nearest outcrop of typical Wolf Creek conglomerate observed occurs east of the field along the State highway, half a mile north of Coryville, in Eldred Township. Red shale occurs a short distance above it, but none was observed below it.

Southwest of Bradford in the Venango district, the Cattaraugus formation is represented by the Venango Oil Sand group as originally defined by Carll(6), the Tuna, Salamanca and Wolf Creek conglomerates corresponding to the First, Second and Third Venango oil sands respectively.

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(3) Glenn, L. C., Devonic and Carbonic formations of southwestern New York: New York State Museum Bull.69, 1903, pp.980-981.

(4) Ashburner, C. A., The Geology of McKean County; Pennsylvania Second Geological Survey, Report R, 1880, pp. 68-69 and 167.

(5) Glenn, L.C., idem. p. 973.

(6) Carll, John F., The Geology of the Oil Regions; Pennsylvania Second Geological Survey, Report I 3, 1880, p. 130.

Chemung group. The Chemung group in northwestern Pennsylvania includes all the strata between the Cattaraugus formation and the Portage group. Only the uppermost portion of this group is exposed in the Bradford district. D. Dana Luther, on the evidence of fossils, placed the bottom of the Chemung at the base of the Long Beards Riffs sandstone which crops out along Genesee River, in northern Allegany County, New York.(7)

The upper beds thus included in the Chemung are younger than the Chemung beds of the type locality at Chemung Narrows, west of Chemung, in south-central New York, as the Catskill type of sedimentation began progressively earlier as one goes eastward and southeastward. While the older grouping has been retained by the writer for the present, a revision of the nomenclature now in use will have to be made in the future.

The Chemung group in the Bradford district consists of interbedded greenish-gray and gray shales and sandy shales, fine-grained light gray sandstones, and fine-grained chocolate-brown sandstones. The total thickness is approximately 2100 feet. Sandstones occur more abundantly in the upper and middle portions than in the lower. In the basal portion, layers of grayish-black shale are present which may represent the Dunkirk shale horizon, the equivalent of the Long Beards Riffs sandstone. Marine fossils occur throughout the entire thickness but are much more abundant in the upper half than in the lower.

The oil- and gas-bearing sands of the district occupy an interval of a little over 1,000 feet in the middle of the group. The Bradford First sand, possibly equivalent to the Cuba sandstone of Allegany County, New York, lies about 650 feet below the top of the group and the Haskell or Bradford Sixth about 400 feet above its base. The oil of the famous Seneca oil spring, 1½ miles northwest of Cuba, apparently issues from the Cuba sandstone.

The intervals between the base of the Olean, the top and bottom of the Cattaraugus red beds, and the important sandstones of the Chemung group, respectively, and the top of the Bradford Third sand in the Bradford district are summarized in Table 1. The interval between the base of the Olean and the top of the Bradford Third sand is smallest in the northern part of the district and largest in the southern; that between the top of the Cattaraugus red beds and the top of the Bradford Third, on the other hand, is largest in the extreme northeastern part and smallest in the southwestern part; and that between the bottom of the Cattaraugus and the top of the Bradford Third is smallest in the northeastern part.

Table 1. Intervals between important horizons and the top of the Bradford Third sand in the Bradford district, in feet:

	Average	Minimum	Maximum
Base of Olean	1895	1791	1979
Top of Cattaraugus red beds	1575	1507	1708
Bottom of Cattaraugus red beds	1255	1183	1282
Top of sands:			
Bradford First	610	560	658
Sugar Run	525	483	559
Chipmunk	440	384	484
Bradford Second	325	284	390
Harrisburg Run (new name)	230	178	271
Bradford Third	0	0	0
Lewis Run (4th)	100	64	168
Kane (5th)	240	184	309
Haskell (6th)	450	408	511

The Bradford First sand is about equivalent to the Glade sand of the Warren district. The Sugar Run sand may correspond to the Clarendon, and the Chipmunk to the Gartland and Cherry Grove. The Bradford Second sand is represented to the south and southwest by the Sheffield and Cooper sands and the Harrisburg Run by the Kane-sholm. The Bradford Third sand corresponds very closely to the Richburg sand of Allegany County, New York, and the Crandall Hill sand of western Potter County, Pennsylvania. The Haskell sand is usually called the Elk in southeastern McKean County.

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(7) Luther, D. Dana, Stratigraphy of Portage formation between the Genesee Valley and Lake Erie: New York State Museum, Bull. 69, 1903, p. 1009.

Portage group. The Portage group includes the strata below the Chemung to the bottom of the Genundewa limestone as delimited by Clark and Luther in the Genesee Valley section.(8) This classification will require revision in the future.

In the Bradford district the upper half of the Portage group is predominatingly gray to dark gray and greenish-gray shales with some interbedded sandy shales and fine-grained sandstones. Black shales are in the lower half. The group in the district is about 1600 feet thick.

Genesee black shale. The term Genesee applies to the black shales between the Genundewa limestone and Tully limestone.(9) In the Bradford district this formation is 75 to 125 feet thick.

Tully limestone. Throughout north-central Pennsylvania, the Tully limestone is an excellent horizon marker for separating the Upper from the Middle Devonian. It can be recognized as far west as Bradford and Kane where it is less than 5 feet thick. Farther west it disappears entirely.

MIDDLE DEVONIAN SERIES.

Hamilton group. The Hamilton group includes the strata lying between the base of the Tully and the top of the Onondaga limestone. In the Bradford district this group consists of 425 to 500 feet of dark gray and black shales.

Onondaga limestone. The Onondaga limestone, 70 to 100 feet thick, is an excellent horizon marker over the entire Bradford district, and is a very fine, crystalline, light gray to dark brownish-gray, cherty limestone.

LOWER DEVONIAN SERIES.

Oriskany sandstone. The Oriskany sandstone is 15 feet thick, fine to medium-grained, light-gray sandstone, with a good show of oil in the Quinlan deep well, in the town of Olean, Cattaraugus County, New York; 17 feet with no fluids in the Ryder-Scott well, on Chipmunk Creek, in the same county; and 20 feet with a show of oil in the Derrick City deep well, Foster Township, McKean County, Pennsylvania. The Oriskany sandstone feathers out not far north of these wells as it was not encountered in the Hotchkiss well, near Randolph, Cattaraugus County, nor in the Autman well, near Humphrey, in the same county. It is probably absent in the southern part of the Bradford district as no sandstone was present at this horizon in the Zerbe well, 3½ miles west of Port Allegany; nor in the Haywood well, 0.7 mile west of Marvindale; nor in the Kane deep well, south of Kane, in Elk County.

Helderberg group. The Helderberg limestone probably is present in the Bradford district immediately below the Oriskany sandstone but is thin. Lacking samples for study, 60 feet of strata have been tentatively assigned to this group in the log of the Derrick City deep well.

SILURIAN AND ORDOVICIAN SYSTEMS.

As identified in the Derrick City well, these strata consist of 20 feet of magnesian limestone, Cobleskill; 850 feet of interbedded, dense, argillaceous, magnesian limestones, light gray to dark grayish-brown, including beds of anhydrite and rock salt, Salina group; 300 feet of very fine crystalline, brownish-gray to very dark grayish-brown dolomite, Lockport; 175 feet of shale, calcareous in upper part, with a thin bed of limestone near the base, Rochester above, Clinton below; 5 feet of fine-grained gray sandstone, Thorold, (top of Medina group); 82 feet of Red Medina or Grimsby, and 58 feet of White Medina or Whirlpool. The well stopped 120 feet in the red, sandy shale of the Queenston.

GEOLOGIC STRUCTURE.

Regional.

The Bradford district is in the northern part of the Appalachian Plateau province. Structurally this province consists of a broad asymmetrical synclinorium or basin, whose long axis tends in a northeasterly and southwesterly direction with the steeper limb on the southeast side. The central part of the plateau in southeast Ohio, southwest Pennsylvania, and northwest Virginia, is floored with beds of Permian age, which are surrounded by outcrops of Pennsylvanian beds. Mississippian, Devonian, Silurian, and older strata crop out in sequence along the west, north, and east margins of the basin.

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(8) Clarke, John M., and Luther, D. Dana, Geologic map and description of the Portage and Nunda Quadrangles: New York State Mus. Bull. 118, 1908, pp. 46-47.

(9) Clarke, John M., and Luther, D. Dana, idem. p. 49.

Folding. On the southeast the plateau terminates along the Allegheny Front and is joined by the closely folded Appalachians. The southeast limb of the synclinorium in its northern part is modified by a series of rather prominent anticlinal and synclinal folds with axes trending approximately parallel to the long axis of the synclinorium. Although some of the anticlines rise in places to the height of 2,500 feet or more above the adjoining synclines, folds 300 to 800 feet high are more numerous.(10) The folds become less prominent in the central part of the basin and are hardly perceptible on the northwest limb.

The foreland folds have trends approximately parallel to those of the closely folded Appalachians to the southeast. They die out gradually northwest from the Allegheny Front. The same forces which produced the folded and faulted structures of the Appalachian Mountains no doubt caused the development of the foreland folds and the two structural features, therefore, have the same age and origin. The foreland folds represent the diminishing activities of tangential compressive forces which originated to the southeast.

Dip. The regional dip of the surface formations in the Bradford district is slightly west of south. If the correlation of the Bradford Third sand with the Laona sandstone on the outcrop to the north is correct, this horizon descends 1,068 feet in a southerly direction in about 44 miles, or an average of 24 feet per mile. Owing to the fact that most of the underlying formations thicken to the southeast, the regional dip of the deeper strata increases toward the southeast.

Local Structure

Surface structure. The outcropping strata in the Bradford district contain no well-defined key horizons that can readily be traced over the entire area. This, with an absence of abundant outcrops, makes mapping of the surface structure difficult. Also an unconformity, with an irregular old erosion surface at the base of the Olean, further complicates the problem. As a result, the base of the Olean in some places is from 20 to 60 feet lower than nearby outcrops of the Knapp. Besides being an irregular surface, the unconformity also bevels the slightly tilted Knapp and older strata.

The surface structure map, figure 1, drawn on the base of the Olean with a contour interval of 50 feet, therefore, is somewhat generalized, and because of the unconformity probably deviates somewhat from a strict representation of the structure. However, two anticlinal folds with accompanying synclines, merging at the north, stand out clearly enough to justify the conclusion that they are of tectonic origin and were developed in post-Pottsville time. Their trends are parallel to those of the foreland folds. They occur along the northwest margin of this belt of folds and no doubt are part of it.

Subsurface structure. A detailed structure map of the Bradford district, figure 2, has been prepared which shows the elevation of the top of the Bradford Third sand above sea level by means of 10-foot contours. Another map of the district, figure 3, drawn to the same scale as that of figure 1, has been included so that the subsurface structure on the Bradford Third sand can readily be compared with the surface structure. Only the 50-foot contours have been drawn on this map.

The major structural features of the Bradford Third sand in the Bradford district are two asymmetrical anticlines trending northeast and southwest, and converging on the northeast in a broad dome. The anticlines have broad tops with gentle dips toward the northwest and considerably steeper dips toward the southeast. Sherrill has shown that this asymmetrical character is typical of the northern Appalachian foreland folds in general.(11) The anticlines are steeper on the flank facing the more intensely deformed mountains.

Figures 1 and 3 show that the major structures as mapped on the erosion surface at the base of the Olean are essentially parallel to those mapped on the top of the Bradford Third sand. This indicates that the present structural features of the Bradford sand were, in part at least, developed in post-Pottsville time.

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(10) Sherrill, R. E., Symmetry of Northern Appalachian foreland folds: Jour. of Geology, vol. XLII, 1934, p. 226.

(11) Sherrill, R. E., Loc. cit., p. 247.

Figure 2 shows minor configurations on the upper surface of the Bradford Third sand which probably are due largely to depositional conditions and differential compaction. Such features would be still more conspicuous if a smaller contour interval were used.

BRADFORD THIRD SAND

All of the oil and gas production in the Bradford district to date has come from sandstones of Upper Devonian age. From the standpoint of oil production, only one horizon, the Bradford Third sand, is of major importance, although locally over some areas oil and gas have been obtained from the Chipmunk, Bradford Second, Harrisburg Run, Lewis Run, Kane and Haskell sands. These areas are shown in figure 4.

The Bradford Third sand is a chocolate-brown sandstone composed predominantly of fine to very fine angular quartz grains. Occasionally a few well-rounded pebbles of transparent to milky quartz, up to 3 millimeters in diameter, occur scattered through the sandstone. These are mostly in the upper layers and rarely constitute any appreciable volume of the rock.

In thin section, the sandstone presents an interlocking mosaic of fine angular quartz grains. A few flakes of muscovite and biotite and an occasional plagioclase grain are present in nearly all thin sections. Some of the mica flakes are bent around the quartz grains. The biotite has in part been altered to chlorite. A small amount of interstitial clay consisting of an aggregate of sericite, kaolin, and a brown material, in part limonite, occurs between the quartz grains, but is not uniformly distributed. Silica, as a secondary crystalline outgrowth from the original quartz grains, and the small amount of clay mentioned form the bond. Calcite only rarely is present in large enough amount to be an important bonding agent. In most thin sections only one or two grains of calcite can be seen. Occasional small clusters of minute pyrite crystals, clearly of secondary origin, are present. In sections cut perpendicular to the bedding, stratification is frequently faintly indicated by the alignment of the occasional mica flakes and some of the elongated quartz grains parallel to the bedding planes.

The Bradford Third sand, although exhibiting a remarkable continuity and a considerable degree of homogeneity over 84,000 acres of proved territory, is by no means uniform throughout the field. Wide variations in total thickness, and number and thickness of shale partings occur in many places between adjacent properties and even adjacent wells. Cross-bedding, however, appears to be absent. Studies of cores indicate variations in porosity, uniformity and actual size of grains, character and amount of cementing material, permeability, and oil content, both vertically and laterally, in the sand.

A section, and porosity and permeability profiles of the sand, on a property in the north-central part of the field, where excellent results have been obtained by water-flooding, are shown in figure 5. The additional recovery by water-flooding on this particular tract, which had practically reached its economic limit by ordinary methods, amounted to 7,280 barrels of oil per acre or 260 barrels per acre-foot of sand.

Lateral and Vertical Variations.

The Bradford Third sand was deposited over a very much larger area than that occupied by the Bradford oil pool. It is in the latter area, however, that the sand is thickest and most continuous. But even in this area, wide variations exist in total thickness of sand and in number and thickness of shale partings.

The greatest thickness of sandstone is in the northeastern part of the Bradford pool in the area occupied by the Knapp Creek dome, shown in figure 3. Near the head of Indian Creek, the sand body is 118 feet thick and 99 feet of this is sandstone. Here the pores of the upper half of the sandstone were originally filled largely with gas and contain little or no oil. Although over much of this area the sand body has a total thickness of 90 feet, the upper 35 to 40 feet originally contained considerable volumes of gas and little or no oil. The upper or gas-bearing portion of the sandstone is characterized by somewhat coarser grains than the average Bradford Third sand. Slightly coarser layers occur in the underlying oil "pay" also. The upper part of the sand body in most places has a much higher permeability than the lower, being of the magnitude of 120 millidarcys as compared with 5 to 15 millidarcys for normal Bradford Third sand.

To the north, northeast, and southeast of the dome, the sand body thins, the amount of actual sandstone present becomes less and less, and the shale partings increase in number and thickness until, at the margins of the field, comparatively little sandstone remains. To the southwest the sand body has a good development over an area five to eight miles wide for about six miles. This includes the north-central part of the Bradford oil pool. The thickness of actual sandstone usually ranges anywhere from 25 to 65 feet. Commonly it is split into a number of distinct layers by shale partings. The individual layers of sandstone show remarkable uniformity of grain size, porosity, and permeability.

West and southwest of Rixford, another gas-bearing zone, similar to the one on the Knapp Creek dome, was found in the upper part of the sand body on a low dome along a structural nose. Here the upper 20 to 25 feet of sand were gas-bearing, the total thickness ranging from 45 to 70 feet.

In the vicinity of Corwins Corners, the belt of thick sand development splits into two lobes. Along the northwest lobe the thick sand continues in a southwest direction for nearly eight miles over a width of about three miles. In total thickness, and in number and thickness of shale partings, it does not differ materially from the sand in the north-central area.

The thick sand in the southeast lobe also trends in a southwest direction but its thickness is considerably more irregular than in the northwest lobe. The thickest sand occurs in two belts, one about 9 miles long and one mile wide along the northwest flank of the lobe, and another approximately 8 miles long and one mile wide along its southeast flank. An intervening belt of thinner sand about one mile wide separates the two.

Over portions of the southeast lobe, the characteristics of the sand body are very similar to those in the north-central area and the north-west lobe. At several localities, however, there are elongated bodies of relatively thick sandstone containing few or almost no shale partings, on the sides of which the sand thins rapidly and has numerous shale layers interfingering with it. Some of the larger elongated bodies are 8,000 feet or more in length and 1,200 to 1,500 feet wide. Most of them are smaller and the ratio of their length to width is greater. In many places the trend of the longer axis of these sand bodies is roughly parallel to the axis of the lobe. Porosities in excess of 20 percent, as compared to 14 to 16 percent for normal Bradford Third sand, are common, and permeabilities in some places run up to 350 millidarcys. Elongate bodies of sandstone of this type are not confined to the southeast lobe but they are more common along it than in other parts of the field.

A belt 2½ to 3 miles wide, in which the Bradford Third sand is very thin or practically absent, separates the northwest and southeast lobes.

Toward and along the margins of the Bradford pool, the shale layers interbedded with sandstone increase in thickness and the sandstone layers become thinner and fewer, Away from the pool only one or two comparatively thin lenses of sand are usually present at the Bradford Third horizon, and in some places the development of sand is so insignificant that its presence is not recognized by the drillers, and other sandstones above or below it are sometimes taken for it. The thinning in most places is more gradual on the northwest side than on the southeast. To the northwest, however, typical chocolate-colored Bradford Third sand disappears from this horizon a short distance beyond the limits of the pool, but to the southeast and east it can be traced at least as far as southeastern McKean County and northwestern Potter County.

To the northeast, the Richburg sand, the productive horizon of the Richburg oil pool of southern Allegany County, New York, probably lies at the same stratigraphic horizon as the Bradford Third sand. The sand in this pool is very similar to that in the Bradford pool, but the area is smaller.

South of the Bradford pool, the sand is well developed in the Guffey pool along Kinzua Creek and in the Burning Well pool two miles east of Kane. This is as far south as the writer has traced the Bradford Third sand. In the Kane pool proper, this sand is either poorly developed or absent. No sand was observed at its horizon in the Kane deep well. Whether the Third Bradford sand, which yields gas farther south and southwest, occurs at the same stratigraphic horizon as the Bradford Third of the Bradford district, has not yet been definitely established.

Conditions of Sedimentation.

The presence of a very fossilferous cap rock immediately above the Bradford Third sand and the sporadic occurrence of well-preserved marine fossils throughout the entire thickness of the sand body itself, indicate that the sand was deposited under marine conditions.

When the sand was laid down, a shallow Upper Devonian sea covered the area. The shore line of this ancient sea probably was no very great distance to the east and southeast of the district. Streams, rendered sluggish by having to flow across a broad, low-lying coastal plain that bordered this sea on the east, washed into it relatively fine sediments, including fine sand, silt, and clay. The sand accumulated in greatest volume opposite the mouths of the larger streams while the finer material was washed farther out into the sea. Waves and shore currents also played an important role in further sorting the sand from the silt and clay, and in distributing it more widely over the shallow sea floor near the shore. The positions of the mouths of the streams that brought in the sediments, the configuration of the sea floor, tidal currents, and the direction and strength of the littoral currents all were factors in determining the distribution, size, thickness, and trends of the sand bodies as they occur today.

BRADFORD POOL.

The unusually thick sand body at the Bradford Third sand horizon was a factor of major importance in the accumulation of oil in the Bradford pool. Structure, no doubt, had an important influence upon the migration of the oil to its present position because the outlines of the pool conform as closely to the structure as sand conditions permit.

Abour 86 percent of the 84,000 acres of the Bradford pool lie in Pennsylvania and 14 percent in New York. Within the limits of the pool, practically the entire production has come from the Bradford Third sand. On the northwest side several small Bradford Second sand pools either partially or entirely overlap the main pool, but their total area is not more than 500 acres.

The boundaries of the Bradford pool, as well as those of the smaller pools whose production comes from the Bradford Third sand, are shown in figures 2 and 3. The large pool is oblong on the northeast and splits into two prominent lobes on the southwest side. Two gas caps occur in the northeastern area, a large one usually referred to as the Knapp Creek dome and another considerably smaller one which will be referred to hereafter as the Rixford dome. In these two domes, the upper portion of the sand originally contained large volumes of gas and little or no oil. The approximate boundaries of the two gas caps are shown in figure 3.

An estimate has been made of the quantity of oil remaining in the Bradford Third sand after the economic limit by ordinary production methods had almost been reached, and of the total oil originally in the pool. In this connection, the pool has been divided into three parts, namely, the northeast area, the northwest lobe and the southeast lobe. The two gas-bearing areas have been considered separately. Also in each of the three main areas, certain parts were separated in which the sand is somewhat thinner, or of lower porosity, and more interbedded with shale. These areas, which might be considered marginal, are not confined to the edges of the pool; one, for example, divides the southeast lobe longitudinally into two parts.

The entire area had already been divided into squares, one mile on a side, and a great many well records had been obtained for each square in connection with the structure mapping. An average thickness for each square mile was computed from the sand thicknesses shown by the records. Only part of the total thickness of sand shown by the drillers' records, however, is oil-bearing sandstone. A percentage factor was, therefore, applied to the average thickness in each square mile which was based upon the percentage of sandstone shown by the examination of cores and drill cuttings, to be in that part of the field. The average thicknesses for the different areas into which the pool had been divided were then calculated from the above averages. The average porosities and saturations assigned to each area are based upon analyses, made by the writer, of cores considered to be typical of that particular area. The results are tabulated in Table 2.

It is realized that these figures represent only rough approximations but they are believed to be conservative. In view of the fact that the estimate is based upon independently-gathered data and arrived at by a somewhat different procedure, the agreement between it and the estimate of 936,174,000 barrels of oil in place after first drilling and before water-flooding, made by the Pennsylvania Grade Crude Oil Association for the Cole Congressional Oil Investigating Committee, is fairly close. (12) In making the latter estimate about 9,000 acres apparently were omitted which the writer has included under marginal areas. This accounts for part of the difference between the two estimates.

Reserves and Future Life of Pool.

A weighted average recovery per acre-foot of oil-producing sand by present flooding methods has been calculated for each of the different parts into which the Bradford pool can be divided. These averages have been used in estimating the total oil that can be recovered from the pool by water-flooding as now practiced. The results are given in Table 2.

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(12) Cathcart, S. H., Oil and Gas Development in Pennsylvania, 1934; Trans. A.I.M.E. vol. 114, p. 372, 1935.

Table 2. Estimate of oil content of Bradford Third sand, in Bradford pool, after natural production had been removed but before water-flooding started.

Part of pool	Acres	Average thickness of oil-bearing sand (feet)	Average total porosity (percent)	Average saturation (percent)	Barrels of oil	Estimated average recovery per acre-foot by water-flooding (bbls.)	Estimated recovery by water-flooding. (bbls.)
Northeast area	22,500	30	14.4	44	331,790,000	185	124,875,000
Northwest lobe	13,500	29	14.3	44	191,100,000	145	56,767,000
Southeast lobe	14,000	26	15.4	44	191,350,000	150	54,600,000
Knapp dome	7,000	31	13.7	33	76,110,000	80	17,360,000
Rixford dome	1,500	28	13.7	33	14,730,000	80	3,360,000
Marginal areas	25,500	22	13.2	42	241,290,000	85	47,685,000
Total					1,046,370,000		304,647,000
Estimated natural production of Bradford pool					203,600,000		
Total oil originally in Bradford pool					1,249,970,000		

The total production of the Bradford pool by methods utilizing the energy inherent in the reservoir itself is estimated at 203,600,000 barrels, making the total oil originally present in the pool 1,249,970,000 barrels. According to these figures, 16 percent of the oil originally present has been recovered by natural methods and another 24 percent will have been recovered when the entire pool has been watered out by the methods of water-flooding now in use.

Oil recovered at the end of 1936 by water-flooding as distinguished from natural production amounted to 110,250,000 barrels, leaving 194,397,000 barrels still to be recovered by water-flooding. The 1936 production was 14,569,740 barrels. At that rate it will take another 13 years to exhaust the pool.

According to the above estimates, 60 percent of the total oil originally present in the Bradford pool will still remain after the entire pool has been watered-out by the present system of water-flooding. It is hardly conceivable, however, that the present methods of water-flooding will not be still further improved before that stage is reached so that the recovery factor will probably be somewhat larger. The figure given represents an average for the entire pool. In those portions of the field where sand conditions are exceptionally favorable, considerably higher recoveries are already being obtained, but even in these areas large quantities of oil remain in the sand after the economic limit by present methods of production has been reached. Whether it will be possible at some future time to recover any considerable percentage of this remaining oil will depend not only upon future technological developments but also upon economic conditions. The price that can be obtained for the oil will be an important factor.

METHODS AND RESULTS OF WATER-FLOODING

The process of water-flooding consists of forcing water under pressure into the oil-bearing horizon through water-intake wells so located that the bank of oil, which accumulates ahead of the advancing water as it permeates the sand, is forced toward producing wells. The "five-spot" arrangement, in which each producing well is surrounded by four intake wells forming the corners of a square, and occasionally the "seven-spot", in which each producing well is surrounded by six intake wells forming the corners of a hexagon, are the patterns at present used.

In laying out a pattern for a flooding operation, no attention is paid to the location of old wells on the property. These are either pumped along with the new producing wells until they are watered out or they are plugged. Occasionally instead of drilling a new well, an old well, if it happens to fit rather closely into the pattern, may be cleaned out and used either as a producing or as an intake well, depending upon its location.

The production data for several different types of floods are summarized in Table 3. The approximate locations of these floods are shown in Figure 3. Flood No.28 is in the Richburg pool, Allegany County, New York, and Flood No.29 in the Burning Well pool of southern McKean County. Although none of the "five-spot" floods had reached their economic limit at the end of the period for which production figures are given, in the majority of cases such a stage had been reached that the oil remaining to be recovered by the methods now in use would not add appreciably to the total recovery, calculated on a per acre or a per acre-foot basis.

Inasmuch as the total thickness of the Bradford Third sand and the percent of this total thickness which is oil-bearing vary within rather wide limits over different parts of the Bradford field, for purposes of comparison the recovery per acre-foot has been calculated on the basis of the thickness of the oil-bearing sandstone estimated to be present underneath each tract. The average thickness of the entire sand body was calculated from the drillers' records; the percent of it that is represented as being oil-bearing sandstone was determined either from the measurement of cores or from the examination of drill cuttings taken on the property in question or on nearby properties.

Relation of Production of Oil by Water-flooding to Physical Characteristics of Sand.

A close relation exists between the physical properties of the Bradford Third sand and the success attained with water-flooding. The ideal sand for water-flooding, as shown by core studies, appears to be one in which practically all the grains are less than 0.2 millimeters in diameter, the porosities of its different members fall within the limits of 14 and 16 percent, and the permeabilities between 5 and 10 millidarcys and which show an average oil saturation of 45 percent or more.

From the standpoint of permeability core shown in Figure 5 represents an ideal condition. It will be observed from the permeability profile of this core that the maximum permeability is only about 9 millidarcys and that the maximum permeability of each of the important layers of sandstone comprising the sand body is about the same. Flood No.16 on the tract from which this core came yielded an exceptionally high recovery per acre-foot of oil-producing sand with a low water output to oil ratio

In the Knapp Creek gas cap in the northeast part of the Bradford field and the Rixford gas cap southwest of Rixford, the upper part of the Bradford Third sand, which originally contained large volumes of gas and only a little oil, the permeability frequently is considerably higher than that of the underlying oil "pay". In spite of the fact that much care is usually exercised in packing off the gas "pay", trouble from by-passing of the water is experienced in these areas. The water input and water output to oil ratios are high, as shown by Floods 23. 24 and 25. The fact that in Flood No.14, located near the southwest margin of the Knapp Creek gas cap, only 25 percent by volume of the total daily input was being accounted for by the oil and water output after the flood had been in operation for four years, would seem to indicate that large volumes of water are not only entering the gas "pay" under the property but are probably also moving into adjacent areas not yet under pressure. In Flood No.25, only 44 percent of the daily input water was accounted for in the output after the flood had been in operation for 3½ years. In marked

Table 3. Summary of Production Data for Various Types of Floods.

A. Distance between intake and producing wells, in feet.
B. Average thickness of oil-bearing sandstone, in feet.
C. Pressure in pounds per square inch at face of sand in intake wells.
D. Oil recovered per acre, in barrels.
E. Oil recovered per acre-foot, in barrels.
F. Water input to oil ratio for entire period.
G. Water output to oil ratio for entire period.
H. Average daily oil production per well at end of period included, in barrels.
I. Water output to oil ratio at end of period.

Flood No.	Type of flood.	Area in acres	A	B	C	D	E	F	G	H	I
1	Circle	35.9		30	600	5,623	187				
2	Circle	9.7		26	600	3,754	144				
3	Circle	21.8		24	490	5,175	216				
4	Circle	30.7		24	585	3,294	137				
5	Circle	12.3		28	525	4,619	165				
6	Circle	4.0		43	555	5,013	117				
7	Circle	135.0		24	700	3,027	126				
8	Circle	20.2		20	875	2,637	132				
9-W	Circle	16.5		19	700	3,804	200				
9-E	Circle	30.0		24	850	5,694	237				
10	Line	16.6	152	24	700-785	4,275	178				
11	Line	3.5	170	28	675	4,280	153				
14	Five-spot	25.0	190	29	625-1025	6,777	234			.47	
15-I	Five-spot	13.41	180	38	800-1000	5,651	149		1.73	.67	15.0
15-K	Five-spot	1.49	180	36.5	800-1000	8,988	246		1.53	.89	13.0
16	Modified five-spot	3.14		31	760-1050	7,276	235		1.89		
16-D	Modified five-spot	1.32		28	760-1050	7,280	260		.76	1.00	20.0
17	Modified five-spot	13.20	210	34	810-960	7,483	220	4.90	1.71	1.60	12.0
18-S	Five-spot	28.8	200	26	720-970	5,014	193			1.58	
18-N	Five-spot	30.6	200	28	720-970	5,266	188			1.47	
19	Five-spot	4.37	154	38	700	7,131	188		2.85	.60	25.0
20	Five-spot	63.8	152	42	715-835	4,850	115	7.33		1.54	
22	Five-spot	16.38	244	25	1200	2,065	83			1.09	3.11
23-AB	Five-spot	2.9	178	31	940	5,947	192	12.84		1.61	
23-D	Modified five-spot	1.9		34	940	6,211	182			1.35	
24	Five-spot	13.67	223	22	885-1335	1,537	70	26.0		1.44	
25	Five-spot	34.5	224	31	900-1550	1,921	62			.72	
26	Modified five-spot	26.26	193	35	800	4,679	142			3.86	
27	Five-spot	18.0	198		1700	1,620				1.43	
28	Five-spot	72.0	198		540-1200	6,020				.65	
29	Five-spot	24.79	212	34	1500-1600	5,143	151	3.33	.71	1.67	4.11

contrast at the end of four years the daily oil and water output was nearly equal to 80 percent of the input.

The so-called loose streaks that are present in certain parts of the Bradford field, particularly the eastern lobe, but not restricted entirely to it, possess a much higher permeability than the average Bradford Third sand. The results obtained in Flood No.25, located along a narrow belt of highly permeable sand representing such a "loose streak" along the eastern margin of the Rixford gas cap, indicate that in those areas in which the highly permeable layers constitute a large enough percentage of a normal thickness of sand body and possess a sufficiently high oil saturation, satisfactory recoveries may be expected, but that the water input and water output to oil ratios will be much higher than in those areas in which more normal conditions prevail. Floods in such areas will probably reach their economic limit before any layers of sand possessing only average permeability, that may be present, have been watered out.

The degree of saturation of the oil-bearing sandstones is an important factor in determining recoveries. The K-unit of Flood No.15 showed an unusually high recovery per acre-foot of oil-bearing sandstone. Core analyses showed an average oil saturation of 46.5 percent for the top "pay" and 40.0 percent for the bottom "pay". When the flood had about reached its economic limit, 51 percent of the oil, calculated on a per acre basis, had been recovered. The oil "pay" on the D-unit of Flood No.23 possessed an average oil saturation of 36.3 percent. When this flood was approaching its economic limit, 45 percent of the oil had been recovered. In contrast, the oil "pay" in a core from the tract on which Flood No.24 is located possessed an average oil saturation of only 29.0 percent and when this flood was approaching its economic limit, only 22 percent of the amount of oil shown by the core analysis had been recovered. The low recovery on this tract, however, is probably due not alone to the relatively low saturation of the oil "pay" but also to the marked difference in permeability of the various layers into which the sand body is divided.

In a homogeneous inclined stratum of sand, Wycoff, Botset, and Muskat have shown that it would be advantageous to carry on flooding operations up the dip, as under these conditions there is less tendency for cusping or fingering to occur and a more uniform advance of the water is obtained.(12) In much of the Bradford field, however, the dips are so slight that the irregularities in the sand body far outweigh in importance any effect that structure may have on the advance of the water-oil interface through the individual layers of sand that comprise the sand body. The "five-spot" method of water-flooding now in use in the Bradford field is not applicable to an up-structure drive.

The spacing between water input and oil wells now in use has been arrived at largely by experience over a period of years. In some of the earlier "five-spot" developments, distances were as low as 150 feet between water intake and oil wells; now 200 to 225 feet is a more common distance. Table 3 shows that this increase has not resulted in any decrease in oil recovery per acre-foot of oil-bearing sandstone. It has, on the other hand, resulted in a considerable decrease in development costs and hence in production costs. It is doubtful, however, whether it would be advisable to widen the spacing still further on account of the marked variations in the character of the sand within relatively short distances. The presence of irregularities would result frequently in the loss of considerable volumes of oil if too wide spacing were adopted. In exceptionally thick bodies of sand containing numerous shale seams, it may even be advisable to shorten this distance if core analyses show a sufficiently large oil content per acre. The local sand conditions should be taken into consideration in determining the spacing for a particular tract.

With the increase in distance between input and producing wells, pressure at the face of the sand in the intake wells has also been increased. Pressures ranging from 1,000 to 1,500 pounds per square inch with the wider spacing have proved satisfactory in areas where sand conditions are normal. In places where most of the sand possesses a relatively high permeability, as in Flood 26, a lower pressure than the one used probably would have resulted in lower water input and water output to oil ratios and quite probably a greater recovery per acre-foot of oil-producing sand, but the rate of recovery would have been reduced. It has been shown, experimentally at least, that if the rate of production is too rapid, the water will tend to cusp or finger toward the producing well.(13)

With a spacing of 200 to 215 feet between intake and producing wells and a pressure of 1,000 to 1,500 pounds per square inch at the face of the sand in the intake wells, in areas where the sand has a normal development, between 80 and 90 percent of the oil recoverable by water-flooding is obtained during the first four years that the flood is in operation. The ratios of water input to oil for those floods studied ranged from 3.33:1 up to 26:1. Ratios above 10 were confined to floods in areas where the oil "pay" is overlain by a gas "pay". In these areas the quantity of water produced with the oil during the later stages of production was so large that it was not feasible to guage it. In floods with the lower input ratios, the ratios of water output to oil ranged from 0.71 to 2.85 for the periods covered by the production data. Unfortunately, detailed data on water input and output were not kept for Flood No.26, located in an area of highly permeable sand.

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(12) Wycoff, R.D., Botset, H.G. and Muskat, M., The mechanics of porous flow applied to water-flooding problems: Trans. A.I.M.E., vol. 103, 1933, pp. 236-237

(13) Wilde, H.D. Jr., The value of gas conservation and efficient use of a natural water-drive as demonstrated by laboratory models: Production Bulletin no.210, American Petroleum Institute, 1932, pp. 4 - 10.

Intake wells take water most rapidly at the start. The rate then declines, at first relatively rapidly and later much more slowly. Operators sometimes offset this decline by increasing the pressure. A study of the results obtained seems to indicate that little if anything is gained by this practice during the later stages of a flooding operation, as the rate of oil production is not appreciably increased thereby, but usually there is a considerable increase in the water output to oil ratio.

Although delayed drilling of oil wells on the properties studied gave no definite indication of an appreciably greater recovery, it has undoubtedly resulted in a saving in operation costs. The same quantity of oil is recovered in less time and usually the water output to oil ratio is somewhat smaller for the total output.

In K-unit of Flood No.15 only about one-half of the total pore space of the sand was accounted for by the oil shown to be present by the core analysis and the oil which had already been removed. In Floods 17 and 29, data on both water input and output were available for periods of 5 to 5½ years. The fact that in Flood No. 17 the total oil and water output represented only 55 percent of the total water input, and in Flood No.29 only 51 percent would seem to indicate that the entire pore space was not filled with oil and water when first wells were drilled, but that considerable space was occupied by free gas. In the tracts in question, this gas was not segregated in the upper part of the sand body but apparently was distributed throughout the oil "pay".

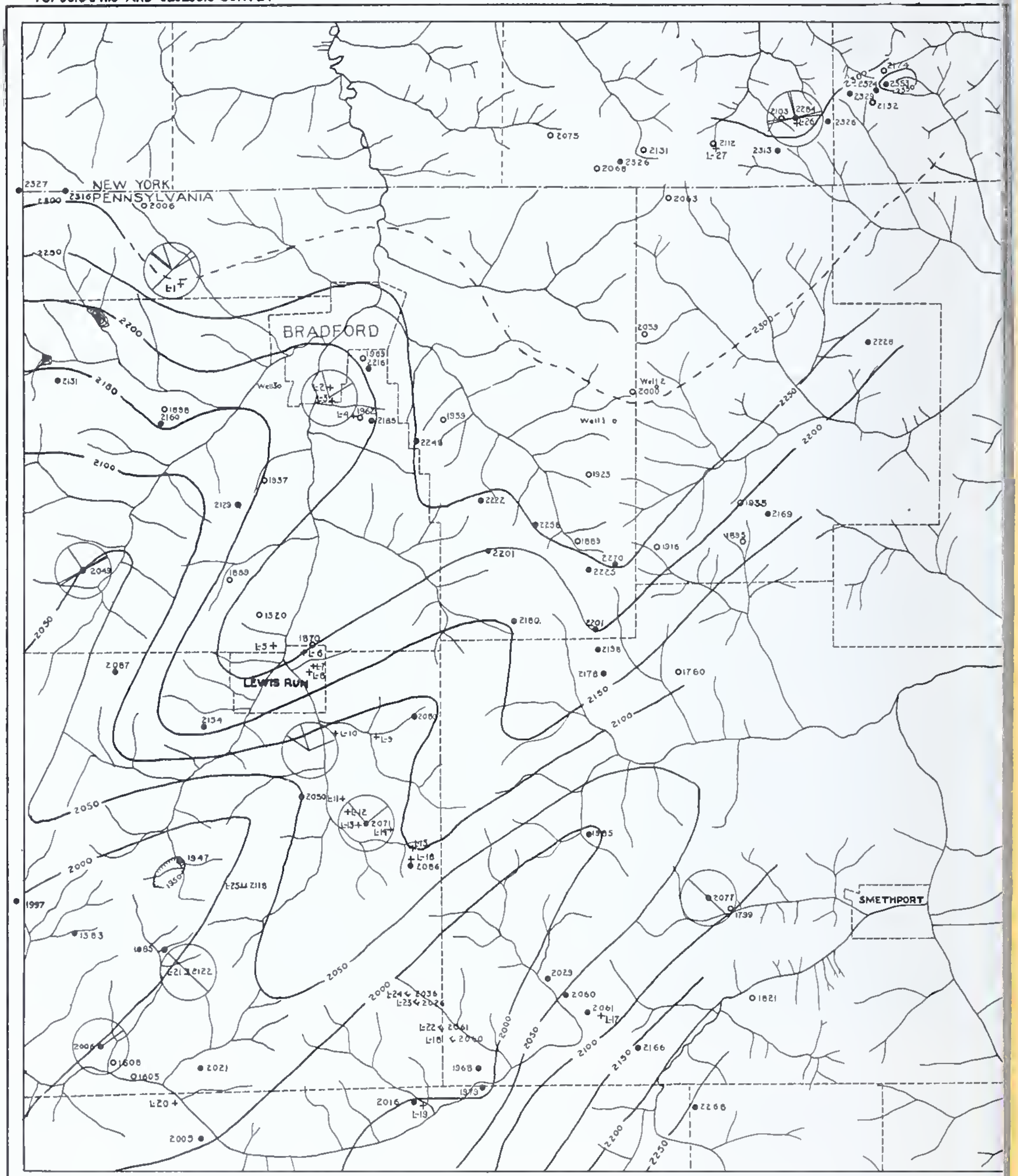
As a general rule, those areas in which the yield per acre by ordinary production methods was high have also given the best results when later subjected to water-flooding. There have been some exceptions to the above rule, however, Flood No.4 is an example. On this tract of 37 acres developed originally by eight wells, the natural production amounted to only 1,141 barrels per acre in contrast to a yield of 3,294 barrels per acre by water-flooding. The tract is near the north edge of the pool. When it was first developed, the reservoir pressure probably already had been reduced considerably and it was therefore not so densely drilled as most parts of the field on account of the low initial production of the wells. As a result the natural production calculated on a per acre basis was low.

In developing old flood tracts care has to be exercised not to locate oil wells at points where an appreciable percentage of the sand body has already been watered out. Attempts to drive oil toward such wells from areas that have not yet been reached by the flood waters have not proven successful. When delayed drilling of oil wells is practiced, trouble may arise if the bank of oil that is built up ahead of the water does not develop symmetrically with respect to the center of the pattern. This may result from irregularities in the sand which cause the water to reach the site of the producing well before the latter is drilled.

Unless the characteristics of the sand body are already definitely known from the results obtained on adjacent properties, it is always advisable to take several cores of the sand on a property before undertaking an extensive water-flooding program. Thicknesses and characteristics of the sand body as determined by the drill and by the examination of the cuttings should be recorded for each well. If this information is available, the behaviour of the input and producing wells can later be interpreted more intelligently. This, in some instances, may indicate points where it may be profitable to drill additional wells.

PENNSYLVANIA
TOPOGRAPHIC AND GEOLOGIC SURVEY

FIGURE 1



LEGEND

- + Locality referred to in text.
- ⊓ Elevation Mercer coal above sea-level.
- ● Elevation base of Olean above sea-level.
- ○ Elevation top of Cattaraugus above sea-level.

OUTCROP AND SURFACE STRUCTURE MAP
OF
BRADFORD DISTRICT

Scale
0 1 2 3 4 5 Miles.

LEGEND

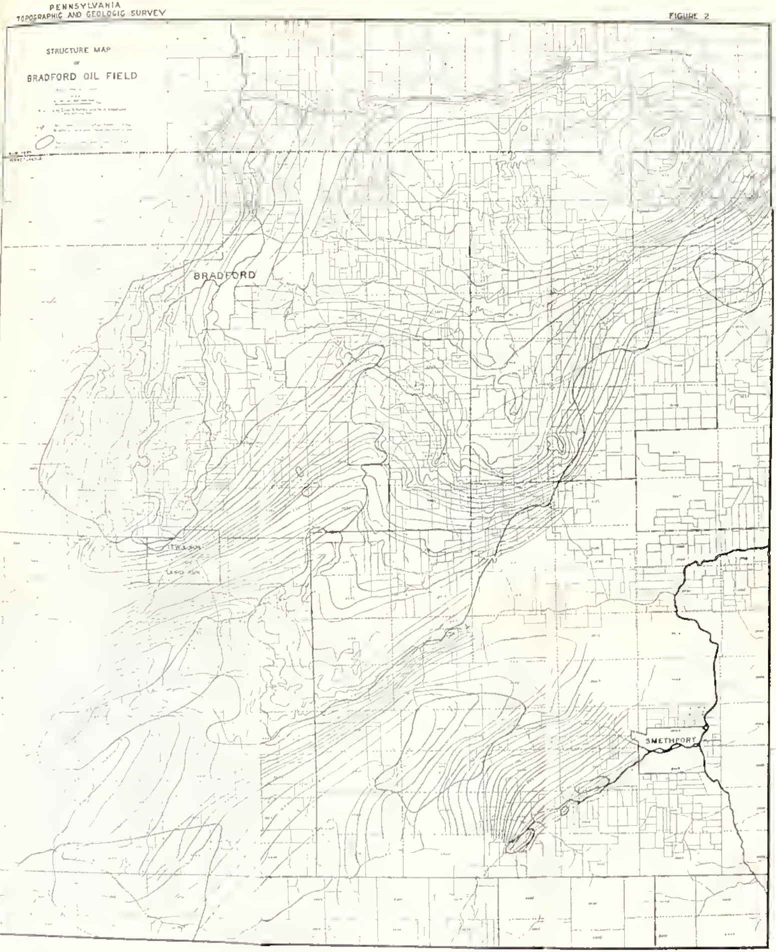
Structure contours on base of Olean.

Strikes of prominent joints.

Chas. R. Fettke.
1934.

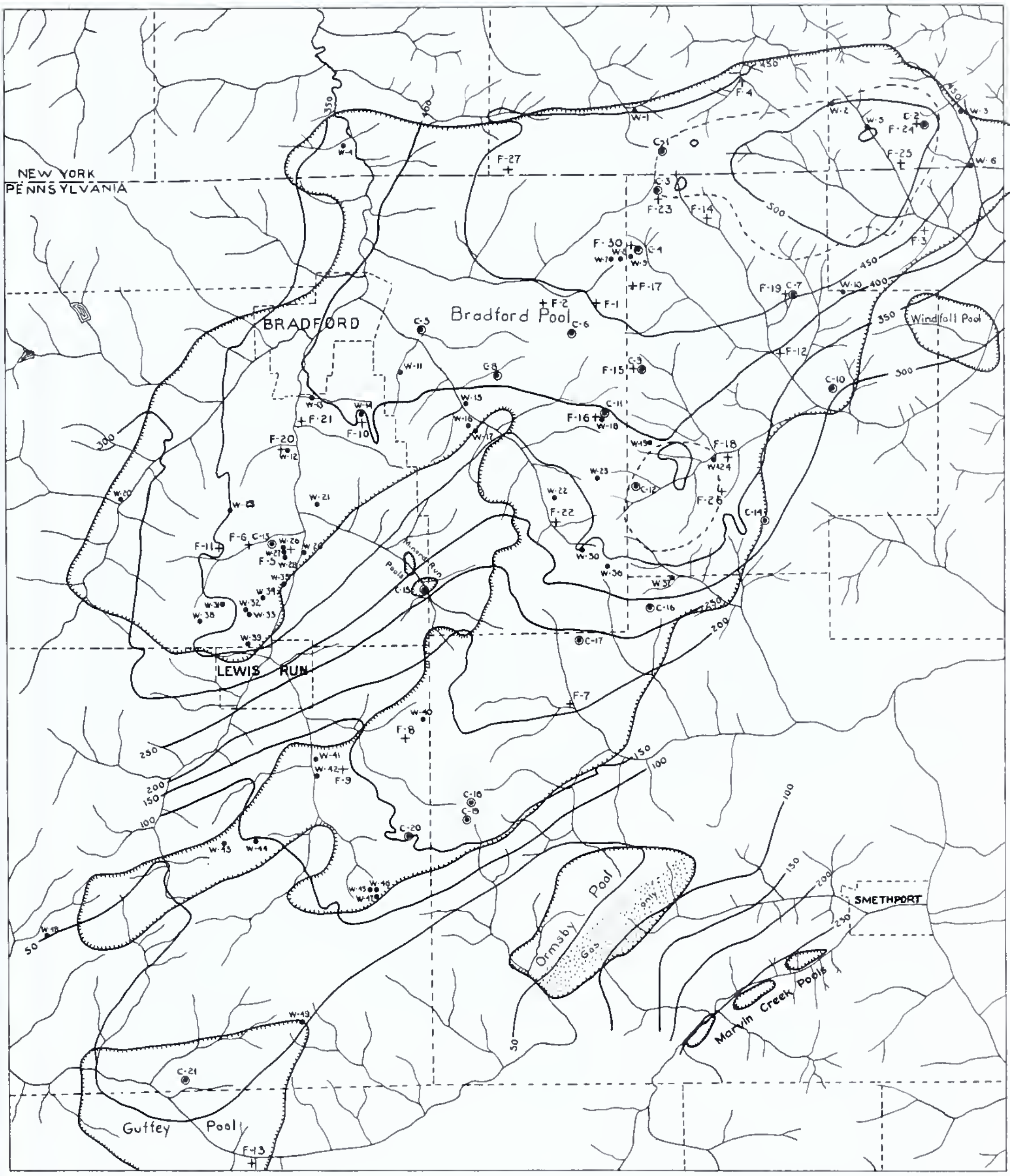
PENNSYLVANIA
TOPOGRAPHIC AND GEOLOGIC SURVEY

FIGURE 2



PENNSYLVANIA
TOPOGRAPHIC AND GEOLOGIC SURVEY

FIGURE 3

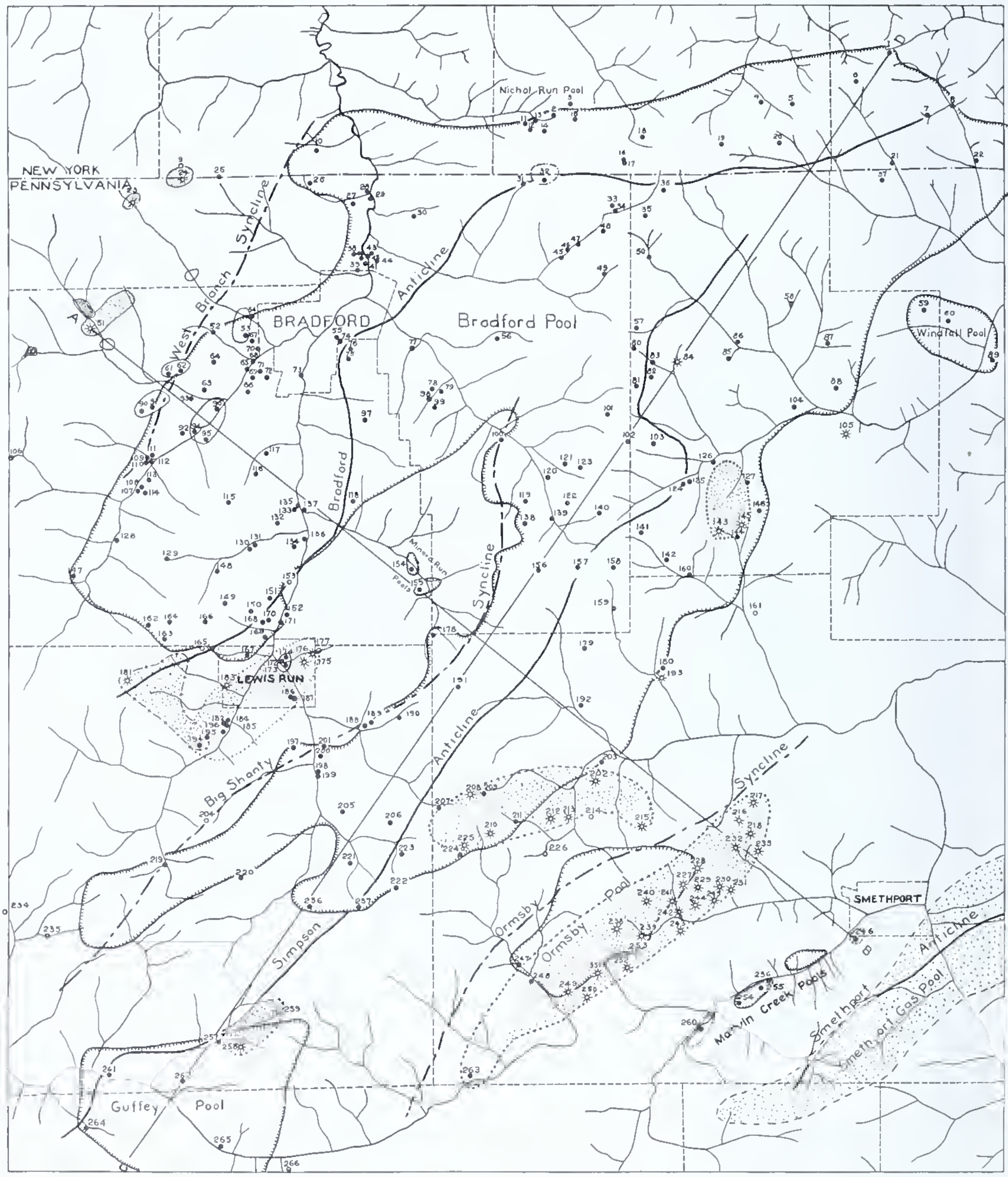

NEW YORK
PENNSYLVANIA
BRADFORD
Bradford Pool
Windfall Pool
Minard Run Pools
LEWIS RUN
Ormsby Pool
Gas only
SMETHPORT
Marvin Creek Pools
Guffey Pool
550
500
450
400
350
300
250
200
150
100
50
LEGEND
Structure contours on top of Bradford Third Sand. Elevation above sea-level in feet.
Approximate limits of production from Bradford Third sand.
Approximate limits of gas sand in upper part of Bradford Third sand
Scale
0
1
2
3
4
5 Miles
LEGEND
C-1 ◉ Core of Bradford Third sand described in text.
W-1 • Cuttings of Bradford Third sand described in text
F-1 + Approximate location of Flood discussed in text

STRUCTURE MAP
OF
BRADFORD DISTRICT

Chas R. Fettke
1934

PENNSYLVANIA
TOPOGRAPHIC AND GEOLOGIC SURVEY

FIGURE 4



OIL AND GAS MAP
OF
BRADFORD DISTRICT

Scale
0 1 2 3 4 5 Miles

LEGEND
Chipmunk Sand production
Bradford Second Sand
Harrisburg Run Sand
Bradford Third Sand
Lewis Run Sand
Kane Sand
Haskell Sand
Gas production only

LEGEND
● Oil Well
☼ Gas Well
○ Dry Hole

Chas. R. Fettke.
1934.

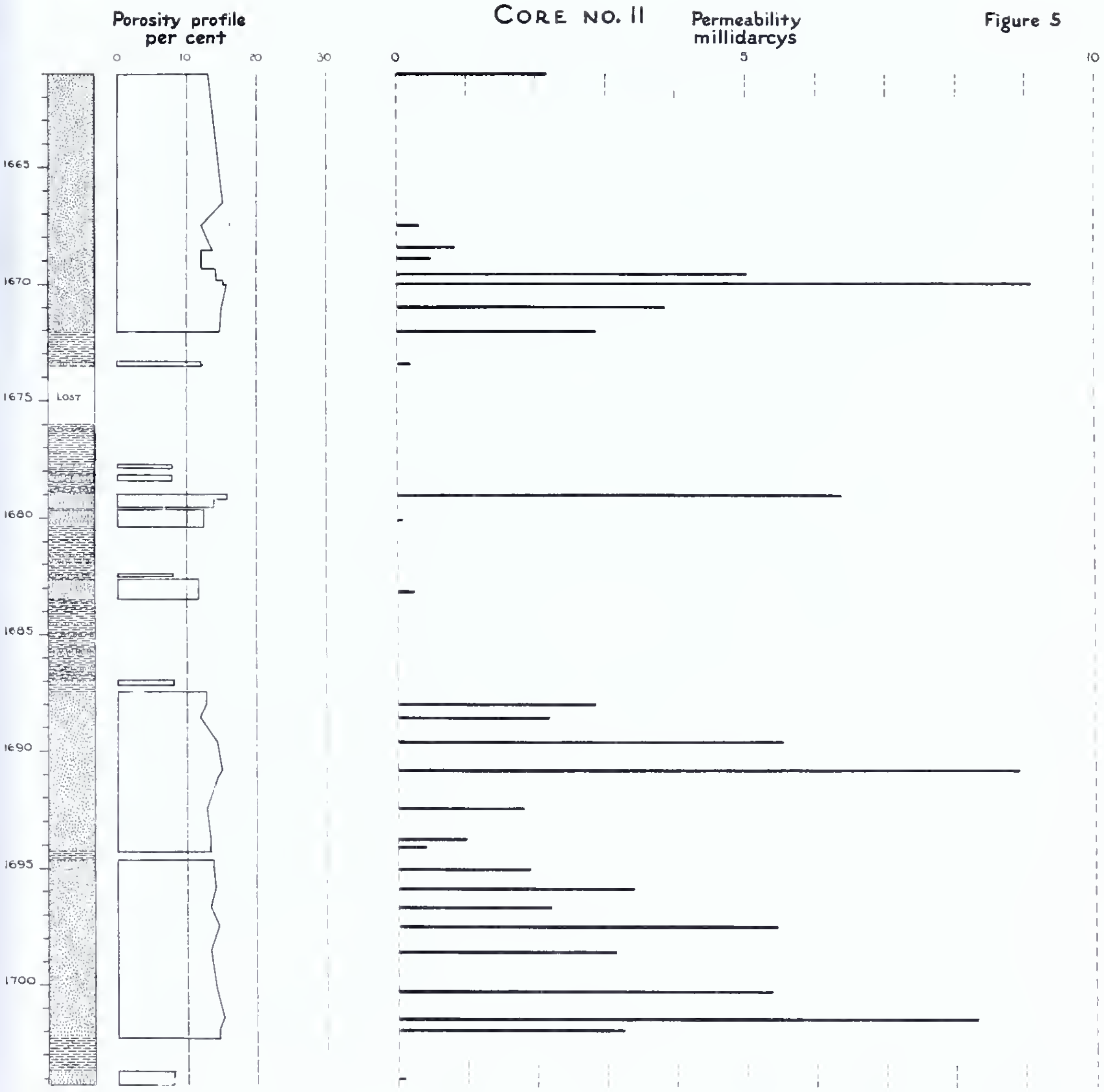


Figure 5

CORE NO. 11
Porosity profile per cent
0
10
20
30
Permeability millidarcys
0
5
10
1665
1670
1675
LOST
1680
1685
1690
1695
1700